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Economic performance of uneven-aged forests analysed with annuities

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For this study, 18 permanent research plots in Switzerland with an area between 0.5 and 2.5 ha that have been installed between 1905 and 1931 were analysed using annuities. The plots cover a wide range of uneven-aged forest-types from pure Norway spruce to classical single-tree selection (plenter) forests dominated by Silver fir in different elevations (575–1810 m a.s.l). The areas have been managed according to an uneven-aged silvicultural system and growth and yield characteristics have been assessed on a single-tree basis every 5–11 years. Net revenues of timber harvesting were computed as a time series from the installation of the plots until today and transformed into net present values and subsequently into annuities for each assessment interval. Three types of annuities: (1) for cutting cycles; (2) forward; (3) backward for the whole assessment period were calculated together with internal rates of return. The results display that annuities were usually positive with an interest of 2 per cent. High elevation (>1400 m) Norway spruce dominated forests as well as heavily overstocked (>900–1000 m^3 ha^{-1}) plots showed the lowest or even negative annuities. The reduction of overstocks lead in the mid-term to an increase, but resulted in a short-term decrease of the annuities. For many of the research plots, especially those in higher elevations, there is a trend towards an increase of the annuities over time. The highest annuities were found in Silver fir dominated selection forests with a growing stock close to or slightly above an equilibrium structure. The backward calculation of the annuities improved for some plots the problem of the strong influence of the value of the initial growing stock. Implications for uneven-aged silviculture as well as for the analysis of the economic performance of uneven-aged and even-aged forests and the application of annuities are discussed in the paper.

Introduction

Annuities

Annuities are an approach to break down net present values calculated for time periods with varying lengths to a yearly basis. The annuity is the yearly constant amount that can be removed within the lifetime of an investment project under capital maintenance (Möhring *et al.*, 2006). The annuity is positive as long as the internal rate of return of the investment is higher than the rate of return used for the calculation. Möhring *et al.* (2006) characterize annuities as a ‘missing link of forest economy’ and emphasize their importance for the calculation of forest investment projects. A detailed introduction into the theoretical background and the calculation of annuities can be found in Möhring *et al.* (2006) and Möhring and Rüping (2008). Manley and Bare (2001) mention annuities within the theoretical framework of the Faustmann-approach.

More recently, annuities have attracted scientific interest for calculating financial losses due to a change of the forest management strategy, specifically under the influence of nature conservation goals (Möhring and Rüping, 2008). Beinhofer (2010b) uses annuities to analyse the effect of the production of different timber qualities for softwood on risk compensation and to compare wide spacing and pruning with traditional plantations of beech and oak (Beinhofer, 2010a). While the application of annuities to integrate risk into silvicultural decision models (Staupendahl and Möhring, 2011) is rather new, a more common way to use annuities is to determine the optimal rotation time (Beinhofer, 2008) instead of the classical Faustmann approach to avoid some of its problems (Möhring *et al.*, 2006) when applying it to practical management issues.

However, looking at these examples of the application of annuities in forestry, it is noteworthy that they are limited to even-aged forests. Many economic investigations in uneven-aged forests are based on theoretical model studies for uneven-aged stands using the Faustmann approach (Chang and Gadow, 2010) or a standard net present value application. The overall database for economic analyses of long-term empirically observed uneven-aged forests, where the application of annuities might be an interesting approach, is rather scarce.

Economics of uneven-aged versus even-aged forests

The economic performance of uneven-aged forests compared with even-aged forests has been subject to an array of investigations (for an overview see Hanewinkel (2002) and Knoke (2012a)). Compared with even-aged forests, uneven-aged forests seem to be economically interesting due to a high percentage of stemwood and large timber and a high timber quality. In addition, there are hints that the risk of biotic as well as abiotic disturbances is rather low in uneven-aged forests (Dvorak and Bachmann, 2001; Hanewinkel, 2001; Hanewinkel *et al*., 2013) due to the complex stand structure and high individual tree stability. Costs for harvesting – despite the limited possibility of mechanized harvesting – planting and young growth tending are as well low in uneven-aged forests as the harvesting is concentrated on large trees and natural regeneration and self-thinning are central elements of forest management in these forests. As there are methodological problems in comparing even-aged to uneven-aged forests from an economic point of view based on empirical investigations, i.e. it is almost impossible to find really similar forest enterprises for both management systems – (Hanewinkel, 2001), model studies have been conducted that show that optimized systems for both management types can produce similar economic outputs. A crucial aspect in these model studies is the assumed level of risk influence in both management systems (Hanewinkel, 2002).

Goal and research questions of the study

The goal of the present study is to analyse the economic performance of long-term observed uneven-aged forests using annuities. Specific research questions linked to this goal are:

(1) Can annuities be used to investigate uneven-aged forests from an economic point of view?
(2) Are annuities able to detect differences in the (site-) productivity of uneven-aged forests?
(3) How do management activities (intensity of harvest, value of the growing stock . . .) affect annuities in uneven-aged forests?
(4) What is the overall profitability of the analysed uneven-aged forests in terms of internal rate of return?
(5) What is the difference between the application of annuities in uneven-aged stands and even-aged stands?
(6) Can annuities be used for recommendations for uneven-aged management from an economic point of view?

Material and methods

Database

Database of the investigation are 18 permanent research plots in Switzerland with an area between 0.5 and 2.5 ha that have been installed between 1905 and 1931. The plots cover a wide range of uneven-aged forest-types from pure Norway spruce (*Picea abies*, (L.) H. Karst.) forests, over mixtures of Norway spruce, European larch (*Larix decidua* Mill.) and Stone pine (*Pinus cembra* L.) to classical single-tree selection forests ('Plenter forests' (Hanewinkel, 2002: 478, Schütz, 2006)) dominated by Silver fir (*Abies alba* Mill.), with admixtures of Norway spruce and European beech (*Fagus sylvatica* L.). The elevation of the research areas varies between 575 and 1810 m a.s.l. From the beginning, the research plots and the surrounding forest stands have been managed according to a single-tree oriented uneven-aged silvicultural system and growth and yield characteristics have been assessed on a single-tree basis every 5 – 1 years. Overall between 10 and 17 inventories were conducted in the different permanent plots. Table 1 gives an overview of the plots including area, dominating species, altitude and the year of the first and most recent assessment. A detailed description of the plots including major growth and yield features can be found in Zingg (2011). We used one even-aged plot of pure Norway spruce to discuss differences in calculating annuities between even-aged and uneven-aged forest stands.

Table 1 Overview of the 18 long-term observed uneven-aged research plots

No.	ha	Spec.	H. a.s.l.	AJ1	AJ2
1015-1	1.7824	Fir, Spr, Be	947	1905	2009
1015-2	1.2373	Fir, Spr, Be	931	1905	2009
1019	1.9880	Spr, Fir	575	1908	1999
1027	1.9852	Fir, Spr	861	1912	2004
1028	1.1826	Fir, Spr, Be	920	1912	2004
1030-1	1.1405	Fir, Spr	910	1914	2011
1030-2	1.8436	Fir, Spr	888	1914	2011
1031	1.3081	Fir, Spr	920	1918	2005
1046	1.9966	Fir, Spr	930	1931	2012
2035	1.9797	Spr, Fir, Be	983	1913	2010
2047	2.4649	Fir, Be, Spr	1060	1931	2011
1041	1.4998	Spr, Fir	1294	1928	2003
1042	2.0024	Spr, Fir	1185	1928	2003
21 293 – 1	1.5261	Spr	1370	1925	2008
21 293 – 2	0.4898	Spr	1405	1925	2008
21 294	1.9960	Spr	1340	1925	2004
1033	0.9947	Spr, SPi, Lar	1810	1921	2009
1034	0.9956	Spr, Lar, SPi	1810	1921	2009

Ha = area of the plot in hectare; Spec = species with; Fir = Silver fir; Spr = Norway Spruce; Be = European beech; SPI = Stone pine (Pinus cembrae); Lar = European larch. First mentioned species is the dominating species. H. a.s.l. = elevation above sea level, AJ1/AJ2 = year of the first (1) and last (2) inventory.

Figure 1 shows the location of the plots in Switzerland. Most of the plots (12) are located in the Emmental region of Central Switzerland (canton Bern), the rest is distributed over Grisons (Southeast CH), Vaude (West CH) and Neuchâtel (West CH).

Gross value of timber and harvesting costs

The gross value of the timber was calculated using the assortment simulator SorSim (Holm *et al*., 2012). SorSim is able to read a list of any trees as a file, divides them into assortments according to a list of given parameters (e.g. following to the Swiss trade customs for roundwood (WVS, 2010) and calculates the gross value based on quality distributions and timber prices.

The stem-form of the logs was modelled using a cubic spline interpolation based on 38 000 measured trees of the Swiss National Forest Inventory (Brassel and Lischke, 2001). The prices for the different assortments are based on recommendations of timber producers of four cantons in Switzerland for the years 2010/2011 (for the most actual version of these prices see Anon (2013)), and the distribution of the timber in different quality classes is based on the regional experience of forest managers. For spruce and fire, between 40 and 50 per cent of the volume is hereby classified either into 'good' quality (B), or the lower C-quality, whereas only 10 per cent belong to the very low D-quality class. A very small amount (5 per cent) of the largest logs (>50 cm mid-diameter) reaches excellent quality (A). For these uneven-aged forests that are managed under a single-tree selection system without pre-commercial thinning and rare extraction of small trees the share of stemwood is particularly high, i.e. usually well above 80 per cent, in many cases >90 per cent.

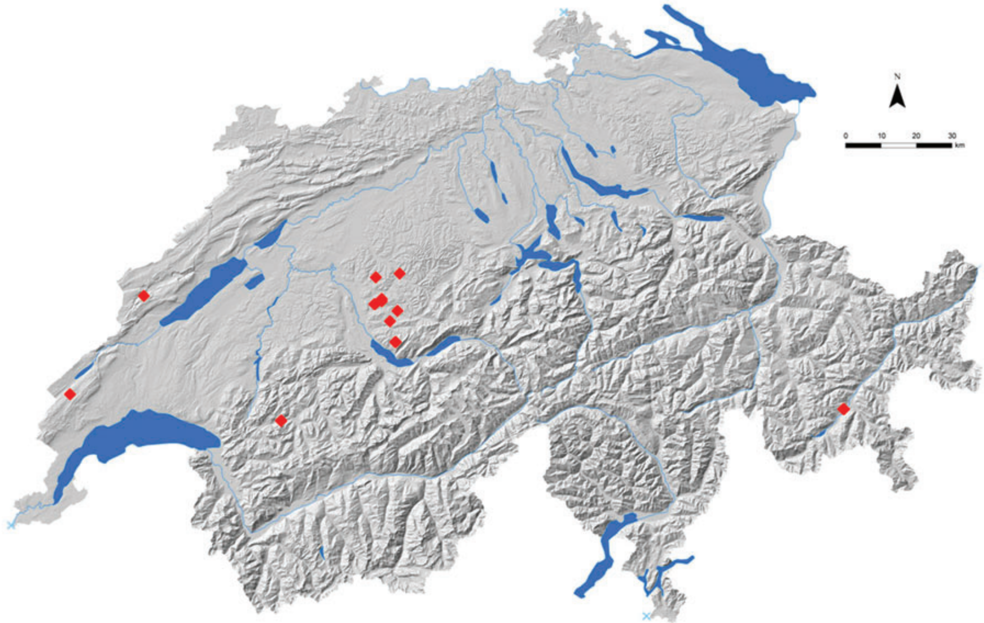

Figure 1 Geographic location of the 18 uneven-aged research plots in Switzerland. Note: in most of the locations there are at least two adjacent plots.

Harvesting costs were calculated using the software HeProMo (Frutig *et al.*, 2009). Adapted to the single-tree harvesting strategy with large trees, the process-chain 'motormanual felling – skidder logging' was adopted. Main input variables for the calculation, such as percentage of stemwood/industrial wood, length of the logs, costs per hour of workforce/skidder, were assumed to be equal for all research plots and fixed as standard input values. This is justifiable as the uneven-aged plots of this study that are dominated by conifers with high amounts of stemwood show very little variance in harvesting costs depending on the share of different assortments. Input variables like mean logging or winching distance were individually determined for each plot based on the terrain situation and were kept constant for the whole observation period. The volume of the remaining and harvested timber, the volume of the mean log and the mean harvested unit according to the simulation of the assortments and percentage of tree species were determined for each inventory in each plot and were used to finally calculate the harvesting costs.

Net revenues of timber harvesting and the value of the growing stock were thus computed as a time series from the installation of the plots until today and transformed into net present values and subsequently into annuities for each assessment interval. In few cases, negative values were observed for the growing stock at the beginning of the observation period, mainly in high elevation plots that started with low standing volumes and small mean diameters. These values were set to zero to avoid artefacts, especially for the forward stepwise calculation of the annuities (see next section, i.e. the more negative the initial value of the growing stock, the higher the overall annuity). Negative values for net revenues of timber harvesting were accepted as necessary investments in the improvement of the stand structure or the stability of the stands.

As the management of the uneven-aged stands does not foresee regular planting, young growth tending or thinning activities (natural regeneration and self-thinning are standard features of the type of uneven-aged managed that is practised in the observed forests) and no costs for this type of activities were reported for our plots, no additional costs were included in the calculation. We restricted our analysis to timber production and thus excluded any fixed costs (e.g. cost of administration), as they would have been impossible to assign to the production function in the different forests that are managed under a multifunctional approach, where the other functions (e.g. recreation) produce an important part of the fixed costs. All calculations were conducted in Swiss Franks (current exchange rate: 1 CHF = 1.1 USD or 0.8 euros).

Calculation of the annuities

We calculated three variants of annuities (equation 1–3):

$$a_{t_b - t_e} = \left(\frac{SV_{t_e}}{(1+i)^{t_e - t_b}} + \frac{h_{t_e}}{(1+i)^{t_e - t_b}} - SV_{t_b} \right) \cdot \frac{i(1+i)^{t_e - t_b}}{(1+i)^{t_e - t_b} - 1} \quad (1)$$

where $a_{t_b - t_e}$ is the annuity for a cutting cycle with starting year t_b and end year t_e, SV is the value of the remaining stand, h is the value of the harvested timber, $t_{k} = t_e$ is the time when the value of the harvested timber was evaluated within the cutting cycle and i is the interest rate.

Variant 1 separately calculated the annuity for each cutting cycle. In this study, the cutting cycle is identical to the inventory interval of the plots. The inventory starts with the marking of the trees that are foreseen for felling. Afterwards all trees are measured and the marked trees are harvested. The cutting cycle is not a fixed value. It varies between 5 and 11 years and is even not stable for a single plot. For Variant 1 the starting point of the calculation for the annuity, i.e. the initial value of the remaining stand at the beginning of the cutting cycle, was updated for each cutting cycle and the time for calculating the annuity was fixed to the duration of the cutting cycle and only the harvesting that took place within the cutting cycle was taken into account.

Variant 1 is the typical cutting-cycle oriented calculation for uneven-aged forests that strongly reacts on short-term changes in harvesting intensity or disturbances and the resulting change of the value of the remaining stand. As the variation of the values over time can be important for this variant, the long-term mean and the standard deviation were calculated in addition.

$$a_{t_b - t_e} = \left(\frac{SV_{t_e}}{(1+i)^{t_e - t_b}} - SV_{t_b} + \sum_{t_k = t_b + 1}^{t_e} \frac{h_{t_k}}{(1+i)^{t_k - t_b}} \right) \cdot \frac{i(1+i)^{t_e - t_b}}{(1+i)^{t_e - t_b} - 1} \quad (2)$$

where $a_{t_b-t_e}$ is the annuity for an observation period with a fixed starting year t_b and a flexible end year t_e that consists of one or more cutting cycles, SV is value of the remaining stand, h is the value of the harvested timber, $t_k = t_b + 1, t_b + 2, \ldots t_e$ is the time when the value of the harvested timber was evaluated within the observation period and i is the interest rate.

Variant 2 (forward calculation, i.e. from the very first year of inventory (e.g. 1905) until year t_k) consecutively calculated annuities with a fixed initial value SV_{t_b} that remained unchanged, by increasingly adding up the discounted value of the harvested timber (h_{t_k}) and taking into account the change of the discounted value of the remaining stand SV_{t_e} until the time of the first inventory. This calculation was repeated until the end of the observation period was reached, i.e. until all cutting cycles were included in the calculation. The first part of equation (1) is an expression of the periodic net present value that is applied in many investigations dealing with investments in forestry (e.g. Knoke and Peter (2002)).

Variant 2 is the standard approach for calculating annuities that is often used for even-aged forests (e.g. to determine the optimal rotation time) and is less sensitive to changes of the harvesting intensity and the value of the remaining stand during the observation period than Variant 1, but is in turn very sensitive to the value of the initial stand at the beginning of the observation period.

$$a_{t_b-t_e} = \left(\frac{SV_{t_e}}{(1+i)^{t_e-t_b}} - SV_{t_b} + \sum_{t_k=t_e}^{t_{b+1}} \frac{h_{t_k}}{(1+i)^{t_k-t_b}}\right) \cdot \frac{i(1+i)^{t_e-t_b}}{(1+i)^{t_e-t_b}-1} \quad (3)$$

where $a_{t_b-t_e}$ is the annuity for an observation period starting with the fixed end year t_e and a flexible starting year t_b that consists of one or more cutting cycles; SV, value of the remaining stand; h, value of the harvested timber; $t_k = t_e, t_{e-1}, \ldots t_{b+1}$, the time when the value of the harvested timber was evaluated within the observation period; i, the interest rate.

Variant 3 (backward calculation from the year of the last inventory (e.g. 2010) to the year t_k) consecutively calculated annuities by adding up the sum of the discounted value of the harvests starting with a fixed end value at time t_e until t_k taking into account the change of the discounted value of the remaining stand at the end of the observation period to the value at time t_k. This calculation was repeated until the beginning of the observation period was reached and all cutting cycles were included in the calculation.

The difference between Variant 2 (forward calculation) and 3 (backward calculation) is that the first one starts with the beginning of the assessment (inventory) of the plots, whereas the latter starts with the end, i.e. with the last inventory. Thus, the starting point for the calculation of the forward Variant 2 of the annuity, which we would consider to be the standard or classical approach, is the standing volume (and the value) of the plot at the time of the first inventory. This first value is – unlike in even-aged stands that start with bare land and are therefore comparable to each other, e.g. across tree species – not the result of a planned management activity and can therefore be arbitrary, i.e. it can either be the result of an excess of value, when the plot has to be developed over a longer transformation period from a more even-aged to an uneven-aged stand or it can be the result of a recent exploitation and the plot has therefore to be developed to a higher volume. For Variant 3, the starting point is the standing volume (and the value) of the last inventory. This starting value of Variant 3 is fundamentally different from that of Variant 2 as it is the result of a planned management activity over decades that in the best case has lead to a standing volume and a stand structure that is close to a steady-state (or equilibrium). As the starting value has great influence on the annuities (as it is deducted from discounted end values of the measurement period), it is interesting to see how a variation of the starting value influences the annuities. The values of the different variants are identical in three cases:

(1) The first value of Variant 2 (forward) is identical with the annuity of the first cutting cycle, calculated according to Variant 1.

(2) The last value of Variant 3 (backward) is identical with the last value of Variant 1

(3) The final value of Variant 2 is identical with the first value of Variant 3 (calculated from the end of the assessment) as they both cover the same values and the same time frame. *However, for most of the cases Variants 2 and 3 are not directly comparable as they refer to different time periods.* We *therefore* calculated mean values and standard deviations for the annuities of the different plots only for Variant 1, whereas we interpreted the values for Variants 2 and 3 as time series. The standard deviation for the different plots for Variant 1 is the result of the variation of the annuities over time for each plot. As the prices are kept constant, the standard deviation is exclusively the results of changes in harvest activities and growth over time and does not include volatile timber prices.

As a default, the annuities were calculated for an interest rate (i) of 2 per cent. A range of 1–4 per cent for i was analysed within a sensitivity analysis.

In addition to the annuities we calculated the internal rate of return for net present values based on the mean value of Variant 1 using an iterative approach (Brealy and Myers, 2003: 105).

In the first part of the Results section we demonstrate the calculation of the different variants of the annuities using the example of one plot.

Results

Variants 1–3 for annuities of a single plot

Table 2 shows inventory results and annuities (Variants 1–3) for Plot 1042. The plot with an area of 2 ha is located in the western part of Switzerland (Canton Vaude) at an elevation of 1185 m (Table 1, Figure 1). The first inventory took place in 1928. Since then, 12 cutting cycles between 5 and 9 years have been assessed until 2003. At the time of the first inventory, the plot was dominated by Norway spruce and has a standing volume of almost 400 m^3 ha^{-1}. Until the 1960s, harvesting in the plot was rather low with a minimum of 24 m^3 ha^{-1} in 1963. After that, harvesting was greatly increased, both in volume per hectare and the mean stem volume which lead to a decrease of the standing volume of the plot to <300 m^3 ha^{-1} and of the mean stem volume from 0.81 to 0.53 m^3. At the same time, the share of Silver fir increased to >45 per cent. The initial net value of the plot in the year 1928 was >10 000 CHF per hectare. This value decreased by almost 50 per cent to ~5100 CHF per hectare in the year 2003. The value of the harvest increased at the same time from <1000 CHF to almost 5000 CHF in 2003 with a minimum at ~500 CHF in the year 1963 and a maximum of >8000 CHF in 1987.

The annuity for the first cutting cycle (1928–1932) for an interest rate of 2 per cent (Variant 1) is calculated in the following way:

$$a_{1928-1932} = \left(\frac{10\,917.34}{(1+0.02)^4} + \frac{948.30}{(1+0.02)^4} - 10\,078\right). \times \frac{0.02(1+0.02)^4}{(1+0.02)^4-1} = 232.07$$

The calculation for Variant 2 is demonstrated for the assessment period 1928–1937:

$$a_{1928-1937} = \left(\frac{10\,938.49}{(1+0.02)^9} + \frac{1633.75}{(1+0.02)^9} + \frac{948.30}{(1+0.02)^4} - 10\,078\right). \times \frac{0.02(1+0.02)^9}{(1+0.02)^9-1} = 161.43$$

Table 2 Inventory data and annuities (Variants 1–3 for i = 2 per cent) for Plot 1042

Year	S/H	ViR (ha)	%_Spruce	%_Fir	Mean Vol	Value (ha)	Cost (ha)	Net Val (ha)	Annuities		
									Variant 1	Variant 2	Variant 3
1928	S	397.44	72.3	27.7	0.81	36 468.24	26 389.89	10 078.35			
1928	H	0.00				0.00	0.00	0.00			186.83
1932	S	384.49	71.7	28.3	0.89	35 870.66	24 953.31	10 917.34	232.07	232.07	
1932	H	41.75	64.9	35.1	0.77	3791.80	2843.51	948.30			181.89
1937	S	384.66	69.6	30.4	0.84	36 056.68	25 118.19	10 938.49	99.65	161.43	
1937	H	41.80	76.3	23.7	1.20	4050.06	24 16.32	1633.75			193.63
1942	S	391.26	69	30.9	0.83	36 981.77	25 627.23	11 354.54	254.43	191.72	
1942	H	46.94	63.1	36.9	1.32	4670.63	2624.15	2046.48			184.60
1947	S	388.40	69	30.8	0.79	36 941.27	25 750.85	11 190.42	28.33	154.50	
1947	H	50.62	57.5	42.4	0.91	4727.89	32 34.57	1493.32			208.87
1952	S	395.84	66.5	33.3	0.81	38 133.17	25 927.85	12 205.32	209.42	163.89	
1952	H	42.05	75.7	24.3	0.77	4035.93	2796.29	1239.63			208.78
1957	S	386.73	66.3	33.4	0.80	37 445.54	25 330.88	12 114.66	70.64	151.38	
1957	H	48.61	57	42.4	0.97	4713.37	2984.76	1728.62			232.83
1963	S	416.70	63.5	36.2	0.88	40 919.21	26 377.42	14 541.79	224.39	160.59	
1963	H	24.28	81.8	17.6	0.57	2308.69	1791.93	516.76			234.78
1969	S	376.56	64	35.5	0.70	36 467.16	25 643.95	10 823.21	−16.80	142.72	
1969	H	101.02	51.7	48.1	1.76	10 538.60	5091.35	5447.26			299.56
1978	S	375.73	62	37.2	0.65	36 529.82	26 226.24	10 303.58	238.51	153.77	
1978	H	100.71	53.9	45.6	1.45	10 366.13	5408.35	4957.78			330.06
1987	S	351.18	57.5	41.4	0.60	33 513.76	25 285.22	8228.54	249.56	162.20	
1987	H	121.21	55.4	44.3	1.49	12 907.34	6387.74	6519.60			387.89
1995	S	325.08	51.3	47	0.53	30 114.47	24 738.96	5375.51	360.23	174.48	
1995	H	117.59	56	43.9	2.24	12 778.24	5420.85	7357.39			420.30
2003	S	293.43	52.1	45.4	0.53	27 383.34	22 241.83	5141.51	420.30	186.83	
2003	H	128.61	27.4	72.1	1.07	12 544.84	7780.64	4764.20			

S/H = standing/harvested volume; ViR = Volume over bark; Mean Vol = mean stem volume; Net Val/ha = Net Value per hectare. All financial results in CHF per hectare.

For Variant 3, we show the calculation for the period 1987–2003 to demonstrate how the backward calculation of the annuity was performed:

$$a_{1987-2003} = \left(\frac{5141.51}{(1+0.02)^{16}} + \frac{4764.20}{(1+0.02)^{16}} + \frac{7357.39}{(1+0.02)^{8}} - 6519.60\right). \times \frac{0.02(1+0.02)^{16}}{(1+0.02)^{16}-1} = 387.89$$

Table 2 shows that the annuities for Variant 1 display a great variation from cutting cycle to cutting cycle until a minimum of −16.80 CHF in the year 1969. After that the annuities for this variant constantly increase to a value of >420 CHF. The change in the harvesting intensity has obviously lead to an increase of the value increment and consequently of the annuities.

This change in the management strategy is not well reflected in the time series of Variant 2 that only shows a slight increase (still below the initial level of the year 1932) after 1969. This is an effect of the rather high standing volume and the value of the growing stock at the beginning of the assessment that very much influences the values for Variant 2 until 2003. Variant 3 shows a constant increase and an overall higher level for the whole time series than Variant 2. We can assume that for this uneven-aged plot with a rather high percentage of Norway spruce, the level of the growing stock of ~300 m^3 ha^{-1} with a mean stem volume of ~0.5 m^3 ha^{-1} is closer to a steady state than the initial value of almost 400 m^3 ha^{-1}, leading to an overall higher productivity.

Calculation of annuities for cutting cycles

Figure 2 shows the results for the mean and standard deviation for the annuities of the 18 research plots as calculated according to Variant 1.

We have grouped the 18 plots into groups according to growth conditions and productivity that are mostly a function of the species composition and growth regions taking into account elevation. In a second step, we looked into the variation of the annuities to detect plots where the management or disturbances had obviously lead to annuities below the potential of the site productivity. Thus, we have detected three different groups of plots:

Group 1 consists of productive uneven-aged, usually mixed stands dominated by Silver fir or Norway spruce in an altitude generally between 800 and 1200 m (extremes: 575 and 1294 m). This group shows annuities that generally exceed 150 CHF ha^{-1} a^{-1}

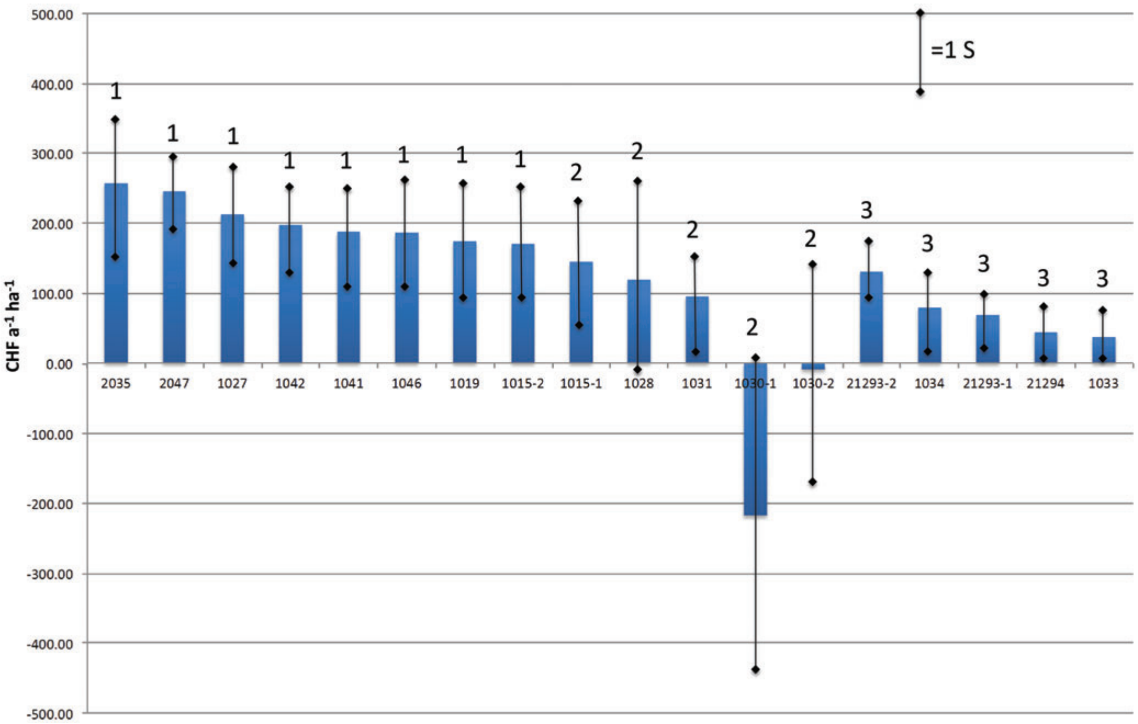

Figure 2 Mean annuities Variant 1 all plots. Annuities for the uneven-aged observation plots assembled in three different productivity groups and decreasing order of annuity for an interest rate of 2 per cent in CHF a^{-1} ha^{-1}. Mean for the whole observation period. Bars depict the single standard deviation (1S) around the mean. Ciphers above the bars indicate the productivity group with 1 = productive, 2 = productive with high S > 100 per cent, 3 = high altitude (>1400 m a.s.l.).

(for $i = 2$ per cent), with a coefficient of variation (CV) below 100 per cent.

Group 2 are stands that grow on comparably productive sites as Group 1 (s. Table 1) and have a similar species composition. However, the high standard deviation of the annuities in this group shows that the management (or other factors such as disturbances) of these stands have lead to a development that prevented these stands from reaching an adequate level of productivity. Group 2 shows annuities below 150 CHF ha^{-1} a^{-1} with a CV clearly above 100 per cent (in extreme cases, e.g. Plot 1030-2 almost 3000 per cent with negative annuities).

Group 3 are stands in high altitudes either dominated by Norway spruce in the sub-alpine zone (>1300 m a.s.l.) or mixed stands of Norway spruce, Stone pine and larch that are typical for the alpine zone (>1800m) (s. Table 1). The plots of this Group 3 display annuities below 100 CHF ha^{-1} a^{-1} or below 150 CHF ha^{-1} a^{-1} but with a CV below 100 per cent (i.e. Plot 2912-2).

To illustrate the effect of management on annuities we show examples of plots that belong to Group 2 (Figures 3 and 4). Especially Figure 3 shows Plot 1030-1 that is like the similar Plot 1030-2 (see Table 1 and Figure 2) a rather extreme example and not necessarily representative for a classical 'Plenter'- system, but it demonstrates well how management strongly influences the economic output in uneven-aged forests.

Figure 3 displays the development of the annuities (Variant 1) for Plot 1030-1, a mixed uneven-aged stand in the Emmental region, growing at an elevation of 910 m dominated by Silver fir (see Table 1). The site clearly points at productive growth conditions and the plot should belong to Group 1. However, looking at the annuity (left y-axis in Figure 3), one can see that the annuities of the stand decrease from a level 200 CHF ha^{-1} a^{-1} to -600 CHF ha^{-1} a^{-1} in the 1960s, and after an increase to the original in the 1980s again decrease to a minimum of -1000 CHF ha^{-1} a^{-1} before the rise again to >400 CHF ha^{-1} a^{-1} in 2010. The development of the standing volume (in m^3 ha^{-1}) of the plot (right y-axis in Figure 3) explains the extreme sequence of the curve. From the 1920s until the 1970s the plot was treated as a 'reserve' with an extremely high standing volume between 850 and 950 m^3 ha^{-1}. This influenced the volume growth of the stand in a negative way and together with increased mortality lead to negative annuities. The reduction of the volume to ~750 m^3 ha^{-1} in the 1970 lead to a short time increase of the annuity, however was not able to prevent a large break-down of the stand with a standing volume below 200 m^3 ha^{-1} in the late 1990s that lead to a sharp decrease of the annuity at the beginning of the abatement of the standing volume. The recovery of the annuity until today is an effect of the dominating 'young' trees after the breakdown with a high volume increment.

Figure 4 (Plot 1028) shows another example where the annuities are strongly influenced by the type of management applied to the plot.

The curve of the annuity (left y-axis in Figure 4) shows strong amplitudes in the 1920s to 40s with minimum values of -400 CHF ha^{-1} a^{-1} and a steady increase from 1955 on. An explanation for the abrupt changes at the beginning of the assessment is the change of the mean stem volume (right y-axis in Figure 4) that in contrast to Plot 1030-1 (Figure 3) was the parameter that has been changed by the management in this plot. The mean stem

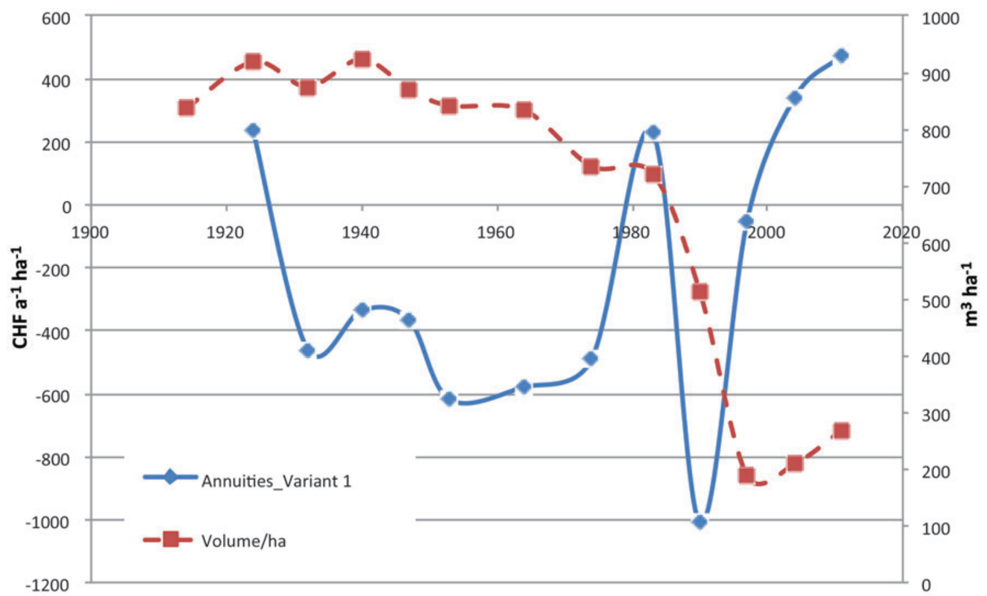

Figure 3 Annuities versus standing volume Plot 1030-1. Annuity for an interest rate of 2 per cent in CHF a^{-1} ha^{-1} (solid line, left *y*-axis) and standing volume in m^3 ha^{-1} (dashed line, right *y*-axis) for research Plot 1030-1 (see Table 1), calculated for Variant 1 (see equation 1). Observation period: 1914–2011.

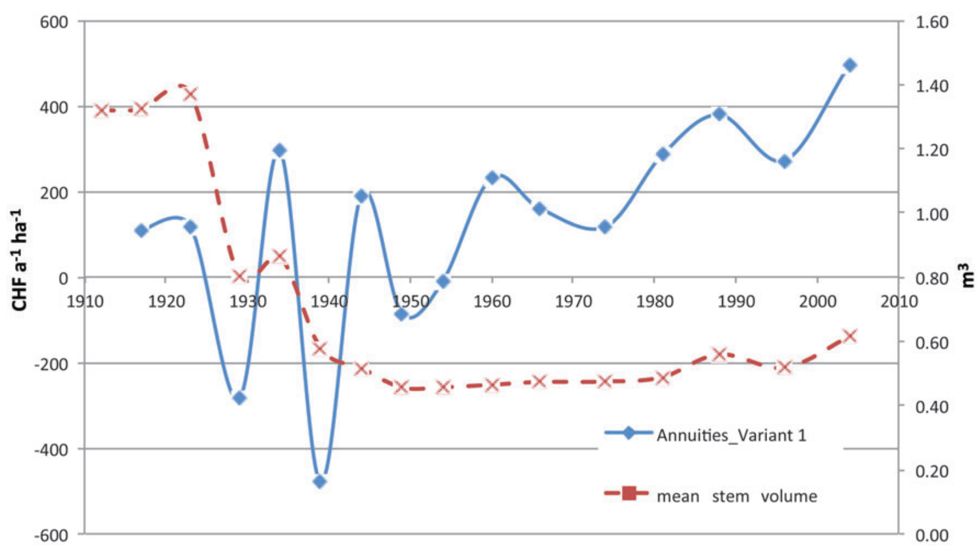

Figure 4 Annuities versus mean stem volume Plot 1028. Annuity for an interest rate of 2 per cent in CHF a^{-1} ha^{-1} (solid line, left *y*-axis) and mean stem volume in m^3 ha^{-1} (dashed line, right *y*-axis) for research Plot 1028 (see Table 1), calculated for Variant 1 (see equation 1). Observation period: 1912–2004.

volume decreases within one assessment period from 1.4 m^3 in 1925 to 0.8 in 1930 and again from 0.8 in 1935 to 0.6 m^3 in 1940 until ∼0.45 in 1950. These sharp decreases that are due to a removal of an excess of large timber to improve the uneven-aged structure of the stand lead to a significant decrease of the value of the remaining stand and consequently to negative values for the annuities. After stabilization of the stand against disturbances due to a lower standing volume and a structure close to the equilibrium from the 1960s on, the annuities constantly increase.

Figure 5 shows the 10-year mean annuities (Variant 1) and the standard deviation for all 18 research plots. Therefore, the different inventory periods for the plots had to be grouped into 10-year age classes. The curve strongly decreases in the two decades 1930 to 1940 and 1970 to 1980. The first minimum can be linked to a first phase of transition towards the uneven-aged structure of the recently installed plots (see Table 1). The effect of the associated silvicultural interventions was already visible in Figure 4. The second decrease in the 1970s is the result of a change of the responsibility

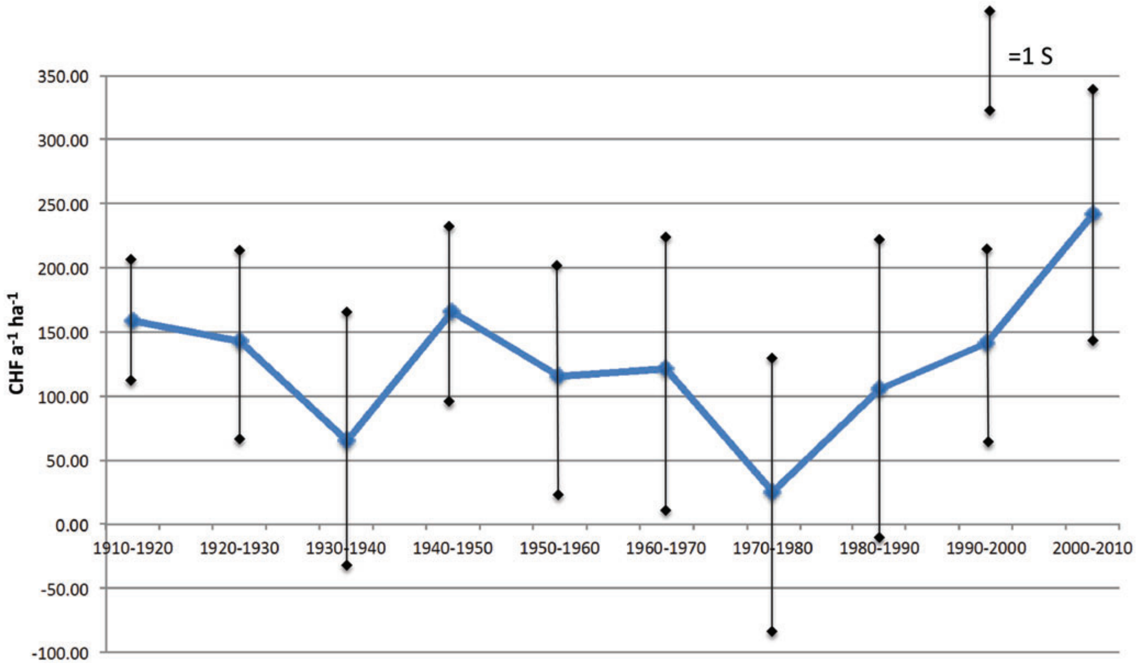

Figure 5 Ten-year mean annuities Variant 1 all plots. Ten-year mean annuities for an interest rate of 2 per cent in CHF a^{-1} ha^{-1} for all 18 research plots (see Table 1), calculated for Variant 1 (see equation (1)). Observation period: 10-year classes from 1910 to 2010. 1 s = single standard deviation.

for the growth and yield network in Switzerland at the beginning of the 1970s. Until the late 1960s the necessary interventions to maintain the uneven-aged structure had been postponed with the consequence of an increase of the standing volume and an excess of large timber. To maintain the uneven-aged structure these interventions were conducted in the 1970s. Like in Figure 4 it is visible how strong changes of the stand structure, either as an overall decrease of the standing volume or the removal of a specific part of diameter distribution (i.e. the large timber) affect the annuities. Since the 1980s, the mean annuities constantly increase revealing the trend that is visible in almost all plots. The standard deviation for all plots increases from the beginning of the observation to a rather high level and is specifically high in decades with low annuities.

Stepwise forward and backward calculation for observation periods

To demonstrate the time series for Variants 2 and 3 (stepwise forward and backward calculation of the annuities) we have chosen examples of plots that demonstrate how the different starting and end values influence the time series for the annuities for these variants and how trends in the development of the annuities are reflected in the different calculation methods.

Figure 6 shows the results of the stepwise calculation of the annuities according to equations 2 and 3 for Plot 1410 (dashed and dotted line in Figure 5). The plot is located at almost 1300 m of elevation a.s.l. and shows a trend towards an increase of the annuities over time (see solid line in Figure 6 representing the annuities for cutting cycles) that can already be detected in Figure 5 and that is especially typical for almost all plots in higher elevations. However, this trend is only hardly visible in the forward calculated annuities (dotted lower curve in Figure 6). The curve for these annuities well represents the trend until the 1970s but then misses the significant increase after the 1980s as it is very much influenced by the values at the beginning of the observation period, similar to the results in Table 2. The curve of the backward calculated annuities (upper dashed line) is very much influenced by the last values for the cutting cycles, therefore well represents the trend since the 1980s but might overestimate the long-term production potential of the site productivity.

Figure 7 shows an example of the stepwise-calculated annuities that displays a different development than the one in Figure 6. Plot 1046 that is depicted here grows at ~930 m a.s.l. and does not show an increase of the annuities over time. The values for the different cutting cycles (solid line in Figure 7) show the typical sharp decrease in the 1970s that have already been discussed (see Figure 5) and a second one in the year 2004 where almost 50 per cent of the standing had been removed after a windthrow. This very much influences the backward-calculated annuities (dashed lower line in Figure 7) that are in that case – except for the last assessment – significantly lower than the forward calculated ones (dotted upper curve in Figure 7).

Table 3 gives an overview of the mean values for the annuities for the observation period and 4 different interest rates (1, 2, 3 and 4 per cent) calculated for cutting cycles (Variant 1). In the last column of Table 3 the internal rate of return for all plots is given.

Table 3 shows that all plots display a positive mean annuity for $i =$ 1 per cent. Almost all plots are positive at an interest rate of 2 per cent (for exceptions – see Figure 2). For $i = 3$ per cent the annuities of the plots of Group 1 are positive and most of the plots of Group 3 are negative. The plots of Group 2 that show extremely high coefficients of variation have negative annuities, whereas the Plots 1028 and 1050-1 of this group still have positive annuities at this interest rate. The values for an interest rate of 4 per cent are negative, except

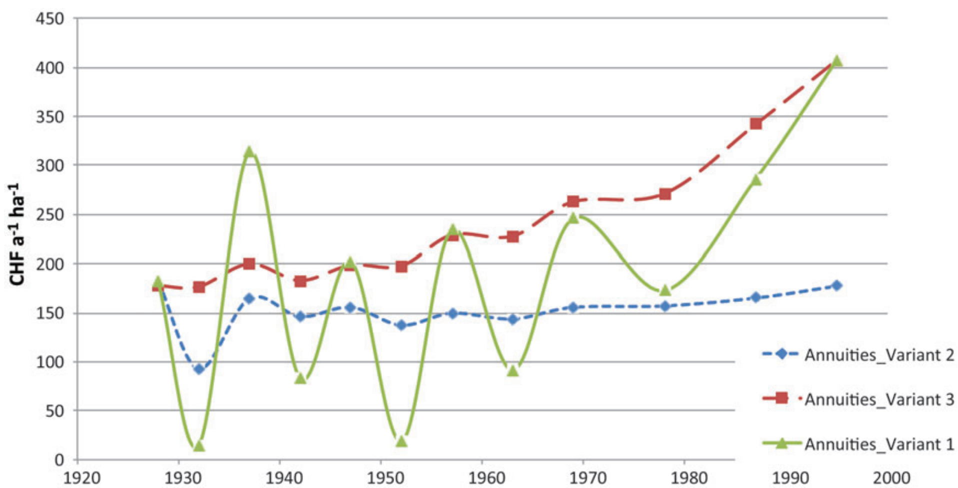

Figure 6 Annuities Variants 1–3 Plot 1041. Annuity for an interest rate of 2 per cent in CHF a^{-1} ha^{-1} for research Plot 1041 (see Table 1), calculated for Variant 1 (solid- line, see equation (1)), Variant 2 (dotted lower line, see equation (2)) and Variant 3 (dashed upper line, see equation (3)) and explanation in the text). Observation period: 1928–2003.

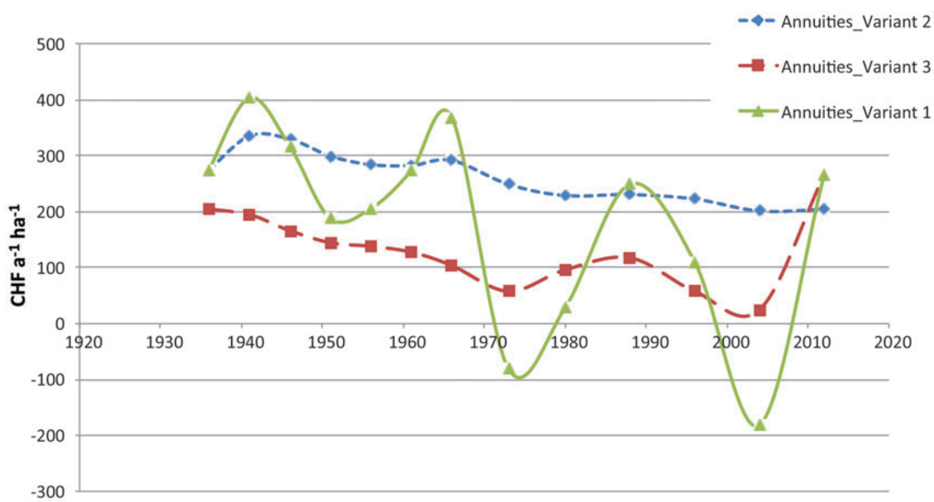

Figure 7 Annuities Variants 1–3 Plot 1046. Annuity for an interest rate of 2 per cent in CHFa^{-1} ha^{-1} for research Plot 1046 (see Table 1), calculated for Variant 1 (solid line, see equation (1)), Variant 2 (dotted upper line, see equation (2)) and Variant 3 (dashed lower line, see equation (3)) and explanation in the text). Observation period: 1931–2012.

for the most productive plots (i.e. 2035 and 2047). The internal rate of return (irr) is between 3 and 4 per cent for most of the productive plots of Group 1 (see Figure 1), is below 2 per cent for the highly overstocked plots (1030-1 and 1030-2) of Group 2, and between 2 and 3 per cent for the subalpine and alpine plots (Group 3). The two most productive plots have internal rates of above 4 per cent. For two plots (1027 and 21 294) the iteration for the calculation of the irr did not properly converge, resulting in unrealistically high internal rates of return that cannot be interpreted.

Annuity of an even-aged forest stand

Figure 8 displays annuities for a typical 0.25 ha research plot of pure Norway spruce that has been observed from 1888 until 1963. The plot was first inventoried with a standing volume of 173m^3 ha^{-1} at the age of 19 and then treated according to a C-grade thinning regime until 1963 to a growing stock of 786 m^3 ha^{-1} before it was destroyed by a windthrow and given up. The solid line in Figure 8 shows the annuity calculated for the different inventory periods with Variant 1. The curve follows the typical growth dynamic of even-aged stands with an unusual peak in the year 1915. The dashed line in Figure 8 shows the stepwise-forward calculated annuities (Variant 2) according to equation (2). The curve starts with negative values and reaches a maximum level of 200 CHF ha^{-1} a^{-1} in the 1940s at an age of the stand of ~70 years where it remains.

The curve shows a development that can – in a similar way – be observed in almost all even-aged stands and is detected in most of the applications that we have referred to in the introduction (Möhring *et al.*, 2006). However, with the given dataset for the uneven-aged stand in our manuscript (only one forest type with C-grade thinning is used), we should be careful in over-interpreting the results in terms of a comparison between even-aged and uneven-aged. Our study can only show general differences when applying the method to the two different management strategies. For further investigations in terms of comparison of performance we should include a much broader dataset with different forest types and management variants for even-aged forest stands.

Table 3 Mean annuities for the 18 uneven-aged observation plots for four different interest rates (i = 1, 2, 3, 4 per cent) in CHF a^{-1} ha^{-1} calculated for Variant 1 (see equation (1))

No.	Group	$i = 1\%$	$i = 2\%$	$i = 3\%$	$i = 4\%$	irr (%)
1015-2	1	270	171	72	−26	3.72
1019	1	335	174	13	−147	3.08
1027	1	260	213	165	118	(6.53)[a]
1041	1	313	188	63	−62	3.50
1042	1	316	198	80	−38	3.68
1046	1	364	186	9	−168	3.05
2035	1	371	257	143	29	4.26
2047	1	361	246	132	18	4.18
1015-1	2	245	145	45	−55	3.45
1028	2	191	120	49	−23	3.68
1030-1	2	145	−218	−579	−940	1.40
1030-2	2	274	−10	−293	−576	1.96
1031	2	237	96	−46	−186	2.68
21 293–1	3	196	69	−58	−184	2.54
21 293–2	3	233	131	29	−72	3.28
21 294	3	63	56	50	43	(>9)[a]
1033	3	102	38	−27	−91	2.58
1034	3	185	80	−25	−129	2.76

irr (%) = internal rate of return. Observation period: 1905–2012;
()[a]= irr is influenced by negative values for growing stock (see text) in the first decades and may therefore be unrealistic.

Discussion

Annuities as a way to analyse uneven-aged forests

Looking at the results of the study in the light of our first research question we can observe that annuities can be a useful tool to analyse the economic performance of uneven-aged forests. Especially with irregular cutting cycles and changing residual growing stocks that are typical for long-term research plots they offer a flexible way of investigating how site productivity and management affects profitability in uneven-aged forests. Chang and Gadow (2010) apply a generalized Faustmann model to uneven-aged forests that allows as well for a variation in cutting cycles and residual growing stock. They reveal that both, length of cutting cycle and growing stock, are sensitive to interest rate, stumpage prices and land value. The results of our study may be used to validate the results of this type of models – after parameterization – as well as those of dynamic optimization models (Tahvonen *et al.*, 2010; Tahvonen, 2011) that seem to be the most adequate approach for uneven-aged forests.

Influence of site productivity and management on annuities

Concerning our second research question, annuities were able to detect differences in site productivity between groups of plots. There was a distinct difference between the productive stands of Group 1 and the high-elevation (sub-alpine and alpine) plots (Figure 2). However, the influence of management (research question 3) strongly influences the annuities and can interfere with site productivity. The analysis of the standard deviation of the annuities calculated for cutting cycles reveals that at least for the productive plots of Group 1, a CV distinctly >100 per cent is a sign that the plots have undergone sudden changes of standing volume or stand

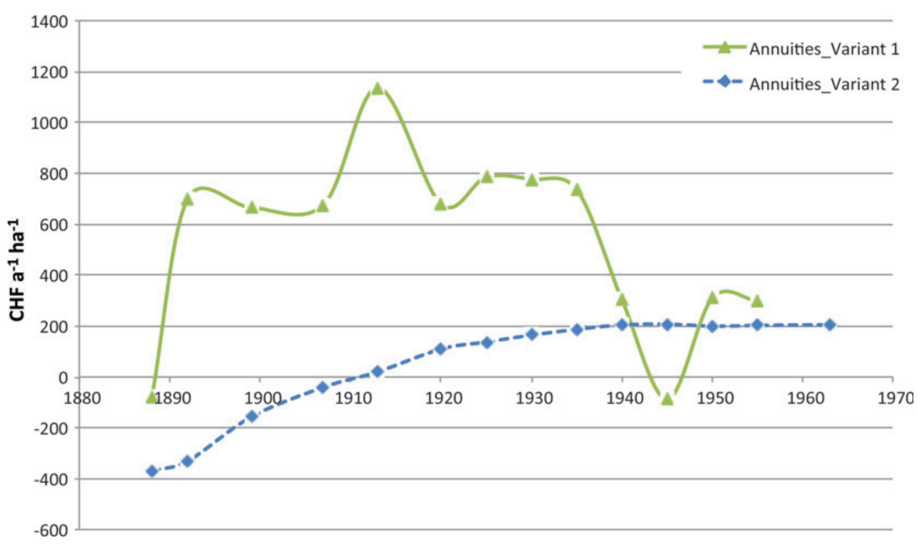

Figure 8 Annuities Variants 1–2 even-aged plot. Annuity for an interest rate of 2 per cent in CHF a^{-1} ha^{-1} for an even-aged research plot of Norway spruce (C-grade treatment), calculated for Variant 1 (solid line, see equation (1)) and Variant 2 (dashed line, see equation (2) and explanation in the text). Observation period: 1888–1963.

structure leading at least temporarily to a strong deviation from an equilibrium. These deviations are always associated with a decrease of the annuity due to an abrupt change of the value of the residual growing stock. Large overstocks as observed in Plots 1030-1 and 1030-2 lead to the lowest annuities, followed by strong interventions, where important parts of large trees are removed within short time. This is visible for the mean value of all observed plots in the decades 1930–1940 and 1970–1980 and can be attributed to a negative influence on value growth of very strong interventions (Zingg *et al*., 2009). This is partly in line with observations by Spiecker (1986) who detected a negative influence of strong interventions on the growth of uneven-aged forests in the Black Forest (SW Germany) especially after drought periods. However, the increase of the annuities in the following decades for many of the plots is a sign that managing uneven-aged forests towards an adequate level of standing volume close to a steady state (equilibrium) will in the long run increase the economic output.

Profitability (internal rate of return) of uneven-aged forests

With respect to our fourth research question, we have observed internal rates of return between 1 and 4 per cent. Most of the productive plots (Group 1) were in a range between 3 and 4 per cent, or even above, which seems to be quite high for Central-European forests that usually range well below 3 per cent. Knoke (2012b) calculated interest rates for European forests between 1 and 4 per cent based on a model approach by Benitez *et al*. (2007). Here we have to suppose that our assumptions concerning the costs lead to an overestimation of the interest rates. To exclude costs for planting, young growth tending and thinning may be justified as these cost-categories do not play a major role in uneven-aged management in Switzerland, which is one of the advantages that uneven-aged forests may have compared with even-aged forests (Hanewinkel, 2001, 2002). At least no such costs have been recorded for our research plots. However, we have to admit that other authors (Duc, 1991; Schori and Mohr, 1999) report about these costs in Swiss selection forests. Furthermore, other fixed costs (e.g. cost of administration) that are not part of our calculation would definitely lead to lower interest rates.

Application of annuities in uneven-aged versus even-aged forests

Looking at our research question five, the study reveals that the application of annuities to uneven-aged stands has specific implications. The calculation of annuities for each cutting cycle is most efficient if we can interpret mean and standard deviation for longer time series as we can detect deviations from the equilibrium and the effect of over- or understocking or the influence of disturbances.

When calculating stepwise-forward annuities, a standard approach for even-aged stands, we have to be aware that the initial growing stock has a large influence on the results. This is different for even-aged stands, as we have shown in Figure 8.

The curve for the even-aged stand is very typical for forests under this management regime (Beinhofer, 2008, 2010a, b; Staupendahl and Möhring, 2011). As we have discussed for Figures 6 and 7, the calculation of the annuities in uneven-aged stands in a similar way may cause problems as it strongly depends on the value of the initial growing stock that is not the result of planned management activities, but whose origin is partly arbitrary or even chaotic. However, within the logic of the annuities, the strong emphasis on the value of the initial growing stock is understandable as it represents the capital that is tied-up in the standing trees and determines the opportunity costs of stand management. The backward calculation shows a better approximation to recent trends but is also depending on changes in volume and stand structure that took place close to last observation. We therefore recommend calculating both types of annuities to interpret long-term trends for the annuities. A third approach – that we did not apply here – could be to first calculate an equilibrium for each stand using a model, e.g. the model for uneven-aged forests by Schütz (1975) and use the steady-state volume as the basis to calculate the annuities. The existing model by Schütz (1975) is based on long-term management data originating from the western part of Switzerland. It includes ingrowth, growth and harvesting rates for diameter classes as well as competition that are combined with an equilibrium model for Silver fir-dominated uneven-aged 'Plenter' forests. The resulting steady state of this model in the form of a diameter distribution could be used as a baseline to calculate annuities.

Conclusions

Implications for management of uneven-aged forests

Looking at our research Question 6 we see some potential to use annuities for recommendations of the management of uneven-aged forests. The overview of the results for all the research plots reveals that the highest annuities can be found for plots that have been managed over longer periods around or even close to an assumed steady state or equilibrium as it can be calculated by models for 'Plenter' forests by, e.g. Schütz (1975). The management can even swap effects of the site productivity as can be seen for plots with a very high standard deviation of the annuities. An excess of standing volume, long-term delayed interventions or sudden removals of larger parts of the growing stock (either by disturbances or as planned cuts to improve the structure) lead to a decrease of the annuities. For stands that are in a phase of transformation from a more even-aged to an uneven-aged structure a recommendation could be to plan rather for a longer than a too short conversion period to avoid abrupt changes in the standing volume and potentially a decrease in growth and economic performance.

Outlook

In this study we restricted the analysis to an empirical investigation of the material and did not develop a model to optimize the management of the observed uneven-aged stands. However, we think that the database allows for the application of a generalized Faustmann model (Chang and Gadow, 2010) or even a dynamic optimization model (Tahvonen *et al*., 2010). Based on a modelling approach we may be able to optimize management for cutting cycles, reserve growing stock or target diameter of species composition using the annuities as the decision variable. Looking at the empirical material, we hypothesize that based on annuities, the relation between reserve growing stock either in terms of standing volume or structure of the growing stock (i.e. share of large timber) and harvested volume should be optimized. At first glance, it seems that the highest annuities result from stands with a comparably favourable relation between growing stock and harvested volume (i.e. a low volume with high timber output). This could lead to new optimized equilibriums (steady states) for uneven-aged forests for a larger site spectrum that are not based on volume growth as decision variable (which is common at the moment) but on an economic parameter. Volume growth cannot be a valid economic parameter by itself as information on the assortments and the timber quality produced has to be included in decision making when managing uneven-aged forests. For the type of annuity that should be used to analyse uneven-aged forests, it is crucial to apply a methodology that avoids the problem of the dominant influence of the value of the initial growing stock at the beginning of an observation period. This is specifically valid when analysing long-term time series. In addition to that, the influence of large disturbances such as storms should be taken into account.

A second aspect that could be subject to further investigations is the analysis of growth trends in different elevations using annuities as an economically interesting parameter. Mainly for the plots in higher elevations we can detect a trend of an increase of the annuity. It is worthwhile to analyse this trend in more depth and whether it can be correlated to climate variables like temperature or precipitation. Uneven-aged forests are particularly suitable for this type of analysis as – once they are close to equilibrium – they do not show the strong influence of management or age as even-aged forests.

Conflict of interest statement

None declared.

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